Process optimization and device variation of Mg-doped ZnO FBARs

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Abstract

Film bulk acoustic resonator (FBAR) is a promising RF device at the frequency ranging from 0.5 to 6.0 GHz due to its small size, high device power and strong potential application in both the cell phone market and sensor application [1–6]. Compared to surface acoustic devices (SAW) [7], FBAR is more powerful and advantageous especially for higher frequencies on 4G and 5G applications. Among the two types of FBAR devices, solid mounted resonator (SMR) is much more robust and higher frequencies on 4G and 5G applications. Among the two types of FBAR devices, solid mounted resonator (SMR) is much more robust and therefore chosen in this work. FBAR built on silicon with Bragg reflector is also closer to CMOS integration [8] than SAW although it may also suffer from temperature sensitivity issues [9]. Just like a CMOS circuit that requires the MOSFET to have a controllable threshold voltage variation, FBAR device variation control is also essential to building an RF circuit such as duplexer in 4- and 5G mobile telecommunication systems. A duplexer demands that each FBAR in the circuit should have wafer-level homogeneity on the central frequency in RF performance as well as Q factor, and so on [10]. Although the FBAR product is commercially available in market, academic studies on the wafer-level FBAR variation and process/design optimization are still relatively weak. In this paper, process variation effects on FBAR device performance were studied via various thin film depositions of Mg-doped MgₓZn₁₋ₓO piezoelectric thin film by optimizing the sputtering power, pressure and ambient gas flow ratios as well as by altering sputtering targets (uniform MgₓZn₁₋ₓO sputtering target with different Mg content and dual sputtering targets of Mg and ZnO with independent control of sputtering power) and by post annealing treatment after the deposition. Design/process interactions and impacts on RF performance variation were studied via multi-FBAR device layouts in different sizes, locations and orientations on the same mask/wafer. Research work on FBAR wafer-level/wafer-to-wafer variation can be helpful to both the academic research study and industrial practice. RF characteristics

1. Introduction

Film bulk acoustic resonator (FBAR) is a promising RF device at the frequency ranging from 0.5 to 6.0 GHz due to its small size, high device power and strong potential application in both the cell phone market and sensor application [1–6]. Compared to surface acoustic devices (SAW) [7], FBAR is more powerful and advantageous especially for higher frequencies on 4G and 5G applications. Among the two types of FBAR devices, solid mounted resonator (SMR) is much more robust and therefore chosen in this work. FBAR built on silicon with Bragg reflector is also closer to CMOS integration [8] than SAW although it may also suffer from temperature sensitivity issues [9]. Just like a CMOS circuit that requires the MOSFET to have a controllable threshold voltage variation, FBAR device variation control is also essential to building an RF circuit such as duplexer in 4- and 5G mobile telecommunication systems. A duplexer demands that each FBAR in the circuit should have wafer-level homogeneity on the central frequency in RF performance as well as Q factor, and so on [10]. Although the FBAR product is commercially available in market, academic studies on the wafer-level FBAR variation and process/design optimization are still relatively weak. In this paper, process variation effects on FBAR device performance were studied via various thin film depositions of Mg-doped MgₓZn₁₋ₓO piezoelectric thin film by optimizing the sputtering power, pressure and ambient gas flow ratios as well as by altering sputtering targets (uniform MgₓZn₁₋ₓO sputtering target with different Mg content and dual sputtering targets of Mg and ZnO with independent control of sputtering power) and by post annealing treatment after the deposition. Design/process interactions and impacts on RF performance variation were studied via multi-FBAR device layouts in different sizes, locations and orientations on the same mask/wafer. Research work on FBAR wafer-level/wafer-to-wafer variation can be helpful to both the academic research study and industrial practice. RF characteristics
were performed with RF probe station and network analyzer together with simulation tools to investigate the frequency shift with respect to process/design variation. The degree of C-axis orientation and crystalline properties of the Mg\(_{x}\)Zn\(_{1-x}\)O film were studied by XRD in the optimization process of piezoelectric layer.

The motivation of adding Mg in ZnO piezoelectric thin film lies in the enhanced resistivity due to the wider Mg\(_{x}\)Zn\(_{1-x}\)O bandgap and possible tailoring on FBAR resonant frequency [11]. Hu et al. [12] reported that incorporating Mg into ZnO may improve the Q factor in FBAR devices. The sizes of FBAR vary from 0.03 to 0.12 mm\(^2\) (from top to bottom) were designed on the same mask, to compare the wafer-level variation and possible size impacts on RF performance with the aid of varying the Mg ingredient in uniform Mg\(_{x}\)Zn\(_{1-x}\)O sputtering target and of dual target sputtering of Mg and ZnO under independent control.

2. Experimental

2.1. Mask design

Two layers of metals are needed to form FBAR devices as the top and bottom electrodes. Usually both layers need to be patterned based upon the need of device and RF circuits such as a duplexer. In this work, only the top metal is photolithography-patterned to build FBAR devices while the bottom metal is a uniform layer serving as an interconnect. This is sufficient for the purpose of studying the FBAR device wafer-level variation. Shown in Fig. 1, the center and ring metal electrodes form one pair of FBAR devices interconnected via the bottom uniform metal layer. The probing of this FBAR device follows standard GSG (ground-signal-ground) microwave probing patterns (70 μm width with 50 μm spacing). Different sizes of FBAR devices were designed on the same mask, to compare the wafer-level variation and possible size impacts on FBAR devices. The sizes of FBAR vary from 0.03 to 0.12 mm\(^2\) (the area of the center square). The area ratio between the center square and the surround ring areas was kept as 1/10 for all devices.

2.2. FBAR fabrication process

To facilitate the future SOC integration, the substrate was chosen as 3-inch (1 0 0) silicon wafer with thickness of 325 ± 25 μm and the resistivity of 20 Ω cm. Prior to piezoelectric film deposition, Bragg acoustic reflection layer was built with three alternative layers of W and SiO\(_2\) films with thickness of 500 nm and 600 nm, equivalent to the λ/4 resonance wavelength [13]. Their depositing parameters are summarized in Table 1.

The thickness of 90 nm Ti was deposited as bottom electrode on the Bragg reflector and then Mg\(_{x}\)Zn\(_{1-x}\)O thin film was deposited consequently at the same sputtering chamber to ensure a clean adherent surface. Also, shown in Table 1 is the range of process optimization parameters of piezoelectric film such as RF power, ambient pressure, and flow ratio to achieve the best piezoelectric Mg\(_{x}\)Zn\(_{1-x}\)O film. After piezoelectric film deposition, 150 nm-thick top electrodes were deposited and patterned. The 3D-view of FBAR was inspected by Keyence’s VK-X 3D Laser Scanning Microscope, which was capable of performing noncontact profile and thickness measurements with a 0.5 nm z-axis resolution, as shown in Fig. 2.

Highly-ordered crystallographic film with a perfect (0 0 2) orientation is essential to building high quality FBARs, since piezoelectric response is highly dependent on the (0 0 2) orientation of this layer. In addition to the optimization of sputtering conditions listed in Table 1, the following design of experiments were also carried out:

- Using two kinds of Mg\(_{x}\)Zn\(_{1-x}\)O sputtering targets with Mg of 10% and 30% ingredient (in mole) respectively for Mg\(_{x}\)Zn\(_{1-x}\)O thin film sputtering;
- Varying the sputtering power of two independent Mg and ZnO sputtering targets to modify the Mg mole content in Mg\(_{x}\)Zn\(_{1-x}\)O film;
- The dependency of RF performance on FBAR size to improve the crystallization on (0 0 2) orientation in Mg\(_{x}\)Zn\(_{1-x}\)O film.

During the sputtering, a mixture of argon (Ar) (99.999%) and oxygen (O\(_2\)) (99.999%) was used as sputtering gas. The distance between the target and substrate is about 70 mm and target diameter is about 80 mm. The substrate temperature was kept 300 °C.

Table 1

<table>
<thead>
<tr>
<th>Deposition parameters</th>
<th>Mg(<em>{x})Zn(</em>{1-x})O</th>
<th>SiO(_2)</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base pressure (Pa)</td>
<td>&lt; 5×10(^{-4})</td>
<td>&lt; 5×10(^{-4})</td>
<td>&lt; 5×10(^{-4})</td>
</tr>
<tr>
<td>RF power (W)</td>
<td>100–250</td>
<td>180</td>
<td>100</td>
</tr>
<tr>
<td>Ar/O(_2) flow rate (sccm)</td>
<td>40/0–10/30</td>
<td>40/0</td>
<td>20/0</td>
</tr>
<tr>
<td>Sputtering pressure (Pa)</td>
<td>1.0–2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Substrate temperature (°C)</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

Fig. 1. Various size of FBARs ranging from 0.03 to 0.12 mm\(^2\) (from top to bottom) were designed on the same mask fitting the 3" silicon wafer with a total of ∼100 FBAR devices.

Fig. 2. top and 3D Microscope of FBAR device with standard 70-50-60-50-70 μm GSG Pico probe. Electrode material either Al or Au with thickness of 150 nm.
material of the sandwich Bragg reflector is replaced by the air as a perfect acoustic reflection layer below the FBAR active area. The simulation result is illustrated in Fig. 4(b), the piezoelectric film displacement at resonance (when the scanned frequency is at center resonant frequency). It is seen from our simulation that the peak vibrating amplitude of the piezoelectric layer can achieve the range of a few microns.

Assuming a minor lattice modulation by adding Mg element in Mg$_x$Zn$_{1-x}$O film, piezoelectric material parameters of ZnO [14] were used in simulation as a rough estimate of Mg doped ZnO thin film material:

The Coupling matrix:

\[
e = \begin{bmatrix}
0 & 0 & 0 & 0 & -0.048 & 0 \\
0 & 0 & 0 & -0.048 & 0 & 0 \\
-0.567 & -0.567 & 1.320 & 0 & 0 & 0
\end{bmatrix} \text{ C/m}^2
\]

Elasticity matrix:

\[
c = \begin{bmatrix}
2.09714 & 0 & 0 & 0 & 0 & 0 \\
1.2014 & 2.09714 & 0 & 0 & 0 & 0 \\
1.05359 & 1.05359 & 2.1194 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.423729 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.423729 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.442478
\end{bmatrix} \times 10^{11} \text{ Pa}
\]

and the relative permittivity matrix:

\[
\varepsilon = \begin{bmatrix}
8.5446 & 0 & 0 & 0 \\
0 & 8.5446 & 0 \\
0 & 0 & 10.204
\end{bmatrix}
\]

The simulation model incorporates mechanical and electrical losses in the piezoelectric ZnO film, representing the hysteresis in a stress-strain curve and in the polarization versus electric field curve of the piezo-material. Both structural and electrical equations were solved in considerations of the multi-physics piezoelectric effect. The electrical equations are not solved in the metallic aluminum layers because the aluminum has a much higher conductivity than that of zinc oxide and hence the aluminum layers almost act as equipotential regions. The dominant electromechanical coupling is exhibited by the piezoelectric layer only. The admittance is calculated as the ratio of the total current flowing through the piezoelectric material to the voltage across it. It is a complex-valued quantity and the imaginary part reflects the displacement current while the real part reflects the conduction current as well as other losses in the structure. The structural and dielectric loss factors appear as the imaginary components of the mechanical stiffness and relative permittivity respectively. The admittance is then calculated and plot as a function of frequency, in comparison with our experimental data on RF measurements.

3. Results and discussion

3.1. Process optimization of Mg$_x$Zn$_{1-x}$O film

(1) Optimization of sputtering conditions

First, various sputtering conditions such as RF power, sputtering pressures, Ar/O$_2$ ratio were optimized to achieve best C-axis piezoelectric orientation of the Mg$_x$Zn$_{1-x}$O thin film. The target is to achieve a stronger and sharper diffraction peak in XRD as well as its minimum deviation from the (002) 2θ value (34.422° for ZnO). After a series of experiments, the optimized condition on depositing Mg$_x$Zn$_{1-x}$O thin film is chosen as 200 W sputtering power, 2.5 Pa of depositing pressure, and 300 °C of substrate temperature with Ar/O$_2$ ratio of 40:0. The diffraction peak of the obtained Mg$_x$Zn$_{1-x}$O (002) is strong and sharp with FWHM value of 0.4°, and the value of residual stress of multilayer films is 2.07 GPa. One of the XRD chart for the optimization of RF power is shown in Fig. 5 where the optimized sputter power is chosen as 200 W instead of 250 W, even if the peak is higher due to its wider
O2 ratio is 40:0, substrate temperature 300 °C, and pressure 2.0 Pa.

FWHM (Full Width at Half Maximum).

(2) Optimization on Mg content in the Mg0.7Zn0.3O film

Two Mg0.7Zn0.3O sputtering targets with Mg content of 10% and 30% were used to form the Mg0.7Zn0.3O layer under the same sputtering process condition. Table 2 lists the corresponding diffraction peak and 20 value of (0 0 2) orientation, as well as derived FWHM and grain size. The diffraction peak in both cases are very high while the peak position (20) in the case of 30% Mg has more deviation from (0 0 2), agreeing with the result in Zhang’s [15] work that over-dose of Mg in Mg0.7Zn0.3O degrades the wurtzite structure property in ZnO by shifted peak position from (0 0 2) 20 angle of ZnO 34.4°.

Similar approach to achieve different Mg-doping in Mg0.7Zn0.3O is via dual sputtering targets of Mg and ZnO in the same chamber by a fixed RF power of ZnO sputtering target at 400 W while altering the sputtering power on Mg target as 3, 5 and 8 W. Increasing the sputtering power of Mg target adds more Mg ingredient in Mg0.7Zn0.3O film. The XRD result is shown in Fig. 6. The corresponding diffraction peak amplitude, position and FWHM value are compared in Table 3. It is observed that in this approach, overdose of Mg ingredient degrades diffraction amplitude and causes more deviated (0 0 2) orientation, consistent with the previous conclusion that doping ingredient of Mg in Mg0.7Zn0.3O film must be carefully controlled [15] in the optimization process.

Comparing the two methods of Mg-doping, an overall sharper XRD peak is observed (by comparing Table 2 and 3) by the first method (using a uniform Mg0.7Zn0.3O target) than the second (using separate Mg and ZnO sputtering targets) with fairly similar (0 0 2) orientation qualities, and therefore a uniform 10% Mg-doped Mg0.7Zn0.3O sputtering target is chosen to fabricate the piezoelectric thin film in our FBAR device.

(3) Effect of post-sputtering annealing

Samples with the optimized sputtering conditions above were annealed under various temperatures in N2 ambient for 10 min. The XRD results are shown in Fig. 7. It is seen that diffraction peak becomes higher and narrower after annealing yet with more 20 deviation. It is therefore not as conclusive that the annealing has positive impacts for a better (0 0 2) crystallization on ZnO film formation in the process of

Table 2

<table>
<thead>
<tr>
<th>Sputter target of Mg0.7Zn0.3O</th>
<th>20 (°)</th>
<th>Δ20 (from 34.22°)</th>
<th>Height (A.U.)</th>
<th>FWHM (°)</th>
<th>Grain size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%Mg</td>
<td>35.562</td>
<td>1.081</td>
<td>22,496</td>
<td>0.208</td>
<td>58.6</td>
</tr>
<tr>
<td>10%Mg</td>
<td>34.113</td>
<td>−0.308</td>
<td>261,692</td>
<td>0.325</td>
<td>26.8</td>
</tr>
</tbody>
</table>

Fig. 5. The XRD patterns of the Mg0.7Zn0.3O films with different RF powers. Ar/O2 ratio is 40:0, substrate temperature 300 °C, and pressure 2.0 Pa.

Fig. 6. XRD of various Mg-doped ZnO using different sputtering power on Mg target while keeping the sputtering power of ZnO target as 400 W.

Table 3

<table>
<thead>
<tr>
<th>Sputter power</th>
<th>20 (°)</th>
<th>Δ20 (from 34.22°)</th>
<th>Height (A.U.)</th>
<th>FWHM (°)</th>
<th>Grain size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 W Mg</td>
<td>34.176</td>
<td>−0.245</td>
<td>8322</td>
<td>0.395</td>
<td>21.7</td>
</tr>
<tr>
<td>5 W Mg</td>
<td>34.256</td>
<td>−0.165</td>
<td>7829</td>
<td>0.342</td>
<td>27.3</td>
</tr>
<tr>
<td>8 W Mg</td>
<td>34.114</td>
<td>−0.307</td>
<td>3061</td>
<td>0.504</td>
<td>17.4</td>
</tr>
</tbody>
</table>

Fig. 7. Effect of annealing on XRD result of MgxZn1−xO piezoelectric film: refraction intensity and the deviation of 20 from (0 0 2) orientation.

SMR FBAR fabrication. Currently, our FBAR fabrication is based on the samples without annealing, and further research work is ongoing to study the overall annealing impacts on the piezo-electric quality by measuring the RF characteristics of FBAR devices built on these annealed wafers.

(4) SEM on cross sectional morphology of FBAR

With optimized piezoelectric film deposition, various FBAR devices were fabricated and Fig. 8 is a cross-sectional view of Mg0.7Zn0.3O/Ti/Bragg layered structure of SMR FBAR. All layers are clearly visible and the interfaces between Mg0.7Zn0.3O film/Ti/Bragg reflector layers are distinct. Thickness of SiO2 and W layer as well as the bottom electrode Ti layer are close to our target thickness (~500–600 nm and 90 nm). The thickness of Mg-doped ZnO film is ~1.7 μm according to the SEM measurements, close enough to their expected value. The thickness variation is in the range of 1.6–1.9 μm (not seen in this picture) from site to site on the wafer.

3.2. FBAR device variation studies

Various FBARs are characterized to compare the size effect on FBAR devices and the wafer-level and wafer-to-wafer variations on Smith
chart, impedance and phase response by one-port measurement of the reflection coefficient S11. The RF probes and the network analyzer were properly calibrated prior to the measurement. Fig. 9 shows the RF characteristics of different areas of FBARs. There are three sizes of FBARs being evaluated, with area of 0.03, 0.06 and 0.12 mm². Larger FBAR in general may have larger resonance circles in Smith chart and less frequency variation with overall less S11 return loss. This suggests a relatively larger FBAR area may average out the roughness turbulence of the deposited piezoelectric film. Obviously more delicate sputtering process help to reduce this variation and to achieve a good FBAR in smaller areas.

Fig. 10 shows RF measurements on FBAR devices on different locations on the two wafers (the repetition of the RF result (not shown) on the same FBAR is identical). It is seen that with the same process control the central frequency has a roughly 0.1 GHz shift between these two wafers. Within each wafer most FBARs confine their resonance frequencies within 0.2 GHz range with good resonance characteristics. Later simulation indicates that this central frequency variation is mainly due to the thickness variation of MgZnO piezoelectric film. More delicate process control is necessary to confine the central frequency in a tighter range in order to fabricate FBAR-related circuitry such as duplexer on various WIFI and sensor applications. This process variation of the FBARs is fairly homogenous with our consistent fabrication process, and it is also observed that yield level of FBAR devices on one wafer is fairly good (> 90%) just a few FBAR device are good once yet

![Cross-sectional view of FBAR structure with Bragg reflection layer.](image)

Fig. 8. Cross-sectional view of FBAR structure with Bragg reflection layer.

![Characteristics of Mg0.5Zn0.5O based FBARs on one wafer with different FBAR sizes. (a) Smith chart, (b) S11 Return loss. Thin red lines, the blue triangle and the big black symbols are the FBAR samples with area of 0.03 mm², 0.06 mm² and 0.12 mm² respectively.](image)

Fig. 9. Characteristics of Mg0.5Zn0.5O based FBARs on one wafer with different FBAR sizes. (a) Smith chart, (b) S11 Return loss. Thin red lines, the blue triangle and the big black symbols are the FBAR samples with area of 0.03 mm², 0.06 mm² and 0.12 mm² respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

![Wafer-level and wafer-to-wafer FBAR device variations in two different wafers. (a) Impedance and (b) Phase. Red solid lines are FBARs from wafer#1; blue dashed square are from FBARs in wafer#2.](image)

Fig. 10. Wafer-level and wafer-to-wafer FBAR device variations in two different wafers. (a) Impedance and (b) Phase. Red solid lines are FBARs from wafer#1; blue dashed square are from FBARs in wafer#2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
The thickness variation of the piezoelectric film plays a key role in controlling the central resonant frequency range in FBAR devices, which in the end affects the yield of the successful FBAR duplexer circuitry. Our optimized FBAR process control renders a 1.6–1.9 GHz wafer-level thickness variation and this causes a 1.8–2.1 GHz wafer-level resonance frequency variation as well as wafer-to-wafer variation. Impact of film thickness on resonant frequency variation is verified by multi-physics computer simulation. The sizes of the FBAR devices only affect the amplitude of the resonance peaks. Regarding to the Mg-doping effect in Mg$_x$Zn$_{1-x}$O piezoelectric film, the amount of Mg in Mg$_x$Zn$_{1-x}$O film during the sputtering process must be properly controlled within 30% to keep the piezoelectric quality. The average acoustic speed of the Mg-doped ZnO film is 6870 m/s with the estimated range of 5760–7980 m/s. Although the average speed is slightly better than that of pure ZnO film (6330 m/s), the enhancement is not as conclusive as the estimated speed variations caused by process variation of the piezoelectric film.

**3.3. Simulation analysis**

The impacts of the piezoelectric film thickness and the FBAR size on S11 response are analyzed via computer simulation. Fig. 11 shows the simulated S11 response by varying piezoelectric thin film thickness and FBAR device size. It is seen from the simulation (Fig. 11(a)) the frequency variation between 1.8 and 2.1 GHz correlate to the thickness variation of 1.6–2.1 μm, in consistent to the experimental data in Figs. 9 and 10, indicating that the frequency shift on the peak resonance in S11 is mainly attributed to the thickness variation and a thicker piezoelectric film induces a lower resonant frequency. The size of the FBAR devices The dependency of RF performance on FBAR affect the amplitude of the resonance peaks shown in Fig. 11(b); this is fairly consistent with the data shown in Fig. 9(b), where we observed a lower amplitude for smaller FBAR devices.

**4. Conclusions**

The thickness variation of the piezoelectric film and the FBAR size on S11 response are analyzed via computer simulation. Fig. 11 shows the simulated S11 response by varying piezoelectric thin film thickness and FBAR device size. It is seen from the simulation (Fig. 11(a)) the frequency variation between 1.8 and 2.1 GHz correlate to the thickness variation of 1.6–2.1 μm, in consistent to the experimental data in Figs. 9 and 10, indicating that the frequency shift on the peak resonance in S11 is mainly attributed to the thickness variation and a thicker piezoelectric film induces a lower resonant frequency. The size of the FBAR devices The dependency of RF performance on FBAR affect the amplitude of the resonance peaks shown in Fig. 11(b); this is fairly consistent with the data shown in Fig. 9(b), where we observed a lower amplitude for smaller FBAR devices.

**Acknowledgement**

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**References**


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